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Oceans

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EXECUTIVE SUMMARY

Global warming as projected by Working Group I of the IPCC will have an effect on sea-surface temperature (SST) and sea level. As a consequence, it is likely that ice cover and oceanic circulation will be affected, and the wave climate will change. The expected changes affect global biogeochemical cycles, as well as ecosystem structure and functions, on a wide variety of time and space scales; however, there is uncertainty as to whether extreme events will change in intensity and frequency. We have a high level of confidence that:

- Redistribution of SST could cause geographical shifts in biota as well as changes in biodiversity, and in polar regions the extinction of some species and proliferation of others. A rise in mean SST in high latitudes should increase the duration of the growing period and the productivity of these regions if light and nutrient conditions remain constant.
- Sea-level changes will occur from thermal expansion and melting of ice, with regional variations due to dynamic effects resulting from wind and atmospheric pressure patterns, regional ocean density differences, and oceanic circulation.
- Changes in the magnitude and temporal pattern of pollutant loading in the coastal ocean will occur as a result of changes in precipitation and runoff.

We can say with a lesser degree of confidence that:

- Changes in circulation and vertical mixing will influence nutrient availability and primary productivity, thereby affecting the efficiency of carbon dioxide uptake by the oceans.
- The oceans' uptake and storage capacity for greenhouse gases will be affected further by changes in nutrient availability in the ocean resulting from other changes in precipitation, runoff, and atmospheric deposition.
- Freshwater influx from the movements and melting of sea ice or ice sheets may lead to a weakening of the global thermohaline circulation, causing unpredictable instabilities in the climate system.

It is presently uncertain whether the frequency and severity of tropical cyclones will increase due to climate change.

The most pervasive effects of global climate change on human uses of the oceans will be due to impacts on biotic resources; transportation and nonliving resource exploitation will be affected to a lesser degree. We can say with a high level of confidence that:

- Increased coral bleaching will occur as a result of a predicted 2°C increase in average global atmospheric temperature by 2050.
- Expanded dredging operations will be necessary to keep major ports open in the Northern Hemisphere, which will increase costs.
- The Northwest Passage and Northern Sea Route of Russia likely will be opened up for routine shipping.
- Growth in the marine instrumentation industry will occur as the need for research and monitoring of climate change increases.

We can say with a lesser degree of confidence that:

- Reduced yields of desirable fish species will occur if average primary productivity decreases.
- If the frequency of tropical storms and hurricanes increases, adverse impacts will be generated for offshore oil and gas activities and for marine transportation in the tropics.
- Marine mineral extraction, except for petroleum hydrocarbons and the marine pharmaceutical and biotechnological industries, is insensitive to global climate change.

Adaptation to the impact of climate change on oceans is limited by the nature of these changes, and the scale at which they are likely to occur:

- No adaptive responses to coral bleaching, even on a regional scale, will be available if average global temperature increases 2°C by 2050. However, reductions in land-based pollution of the marine environment, combined with reductions in habitat degradation/destruction, would produce benefits for fisheries, aquaculture, recreation, and tourism.
- Adaptation options will be available for the offshore oil, gas, and shipping industries if the frequency of tropical storms and hurricanes increases. The options include improved design standards for offshore structures, national and international regulations for shipping, and increased technological capabilities to provide early warning at sea. Governments also can increase attention to institutional design for planning and responding to disasters and acute emergencies.
- Where climate change generates positive effects, market-driven needs will create their own adaptation dynamic. However, adaptation policies will be required to control externalities that are market failures. For instance, opening up both the Northwest Passage and the Russian Northern Sea Route for up to 100 days a year—while a boon to international shipping and consumers in East Asia, North America, and Western Europe—will have to be accompanied by policies designed to limit the total burden of pollutants entering the Arctic environment from ports, ship operations, and accidents.

8.1. Introduction

In this chapter, we attempt to assess the impacts of projected regional and global climate changes on the oceans. Climate change will affect the physical, biological, and biogeochemical characteristics of the oceans at different time and space scales, which should modify their ecological structure and functions and is expected to exert significant feedback controls on the climate system. These changes will be in addition to human activities such as land-use changes, industrialization and urbanization, increased food production, habitat modification, transportation of exotic organisms, and releases of pollutants. The present trends of increasing pollution, development, and overuse are reducing the capacity of coastal oceans and semi-enclosed seas to respond to and compensate for environmental changes that might be brought about by a climate change (GESAMP, 1990).

In providing this assessment, we address questions concerning the functions and characteristics of oceans in relation to their human uses, their responses to large-scale global climate change, the range of available mitigation and adaptation response options, and continuing research and monitoring needs.

8.2. Functions of Oceans

The oceans function as regulators of the Earth's climate and sustain planetary biogeochemical cycles. They also are of significant socioeconomic value as suppliers of resources and products, as sinks for wastes, as areas of recreation and tourism, as a medium for transportation, and as a repository of genetic and biological information. To gain a perspective of the oceans' importance, consider that the global ocean industry (all sectors) realizes about 4% of world gross national product (GNP)—approximately $20 trillion in 1988 (Broadus, 1991).

8.2.1. Climate Regulator

The oceans have significant capacity to store heat and are the largest reservoir of the two most important greenhouse gases—water vapor and carbon dioxide (CO_2). The long timescales of vertical circulation in the oceans result in slow turnover of stored heat and CO_2. The properties of oceans are affected by variability resulting from Sun-Earth orbital changes (e.g., seasonal and Milankovitch cycles); interactions among components of the climate system—for example, the atmosphere-cryosphere—modulate these variations and result in climatic variability on other timescales.

Just less than 60% of the Earth's radiative energy from the Sun is received by the ocean, 80% of which is absorbed in the top 10 m of the ocean. Winds and waves mix down a seasonal surface layer of nearly uniform temperature, salinity, and other properties. This layer extends to tens of meters in the tropics and to several hundred meters in high-latitude seas, where oceanic convections are due to the annual cooling of surface waters and where the winds are stronger and the waves larger. The permanent thermocline lies below the seasonal surface layer, down to about 1000 m depth. Circulation down to the upper thermocline is principally wind-driven and is characterized by basin-scale gyres and intensive western boundary currents such as the Gulf Stream and the Kuroshio. The oceans transport about the same amount of heat poleward as the atmosphere (Trenberth and Solomon, 1994), and these western boundary currents are the most important carriers.

The lower thermocline and the abyssal ocean represent nearly 90% of the volume of the oceans, and most of this water is colder than 5°C. It is dominated by thermohaline circulation driven by differences in density. Globally, the oceanic thermohaline circulation can provide a substantial buffer against greenhouse warming. It incorporates both heat and CO_2 from the atmosphere at higher latitudes and releases them at lower latitudes decades or centuries later. Thus, it plays an important role in controlling the distribution of both heat and greenhouse gases and, as a consequence, modulating global climate.

About 57% of oceanic volume is colder than 2°C. Except for the Arctic Ocean and the nearby part of the Atlantic Ocean, these characteristics can only be derived from Antarctic bottom water (Gordon, 1991). Therefore, a significant part of global thermohaline circulation is driven by the formation and sinking of Antarctic bottom water, principally in the Weddel Sea. As a consequence, the Antarctic Ocean is quite important for the global climate, but its role in contributing variability to climate is not understood. Further, changes in the formation of deep water in the North Atlantic are usually considered to be part of the processes by which the Earth moves from an ice age to an interglacial and back again. This process is explained in Box 8-1.

Studies of gases trapped in polar ice cores have shown that the concentration of atmospheric CO_2 has undergone variations that parallel climatic changes (Barnola *et al*., 1987). The strong correlation between variations of polar temperature and atmospheric carbon dioxide concentration in comparison with the Sun-Earth orbit-induced glacial-interglacial cycles strongly suggests the existence of feedback mechanisms involving the interplay of biological, chemical, and physical processes (Watson *et al*., 1990). Because the ocean contains about 60 times more carbon than the atmosphere (Sundquist and Broecker, 1985), variations in atmospheric CO_2 could result from even minor changes in the ocean's physicochemical and biogeochemical characteristics affecting carbon cycling in the sea. Among the proposed explanations for the variability of atmospheric CO_2 contents on these timescales are changes in ocean productivity (Sarnthein *et al*., 1988) and fluctuations in the quantity of carbon stored in the deep sea—which in turn, are related to changes in ocean circulation (Boyle and Keigwin, 1982; Curry *et al*., 1988).

The natural fluxes of the exchange of carbon dioxide among atmosphere, ocean, and land biota are much larger than anthropogenic perturbations (IPCC, 1994). Because of complex oceanic carbonate chemistry, the ocean—compared to its reservoir

Box 8-1. Ocean Conveyor Belt

The "conveyor belt" global thermohaline circulation is driven primarily by the formation and sinking of deep water (from 1500 m to the Antarctic bottom water overlying the bottom of the ocean) in the Norwegian Sea (Figure 8-1; Broecker, 1991). This circulation is thought to be responsible for the large flow of upper ocean water from the tropical Pacific to the Indian Ocean through the Indonesian Archipelago—the Indonesian Throughflow (e.g., Broecker, 1991).

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Figure 8-1: Ocean conveyor belt (after Broecker, 1991).

The global conveyor belt thermohaline circulation is controlled by two counteracting forcings operating in the North Atlantic. The *thermal forcing* (high-latitude cooling and low-latitude heating) drives a poleward surface flow, and the *haline forcing* (net high-latitude freshwater gain and low-latitude evaporation) moves in the opposite direction. In today's North Atlantic, the thermal forcing dominates. When the strength of the haline forcing increases due to excess precipitation, runoff, and/or ice melt, the conveyor belt will weaken (i.e., decrease in both poleward warm surface flow and deep-water formation) or even shut down. The variability in the strength of the conveyor belt will lead to climate change in Europe. Climatic variation in other parts of the global ocean also may be influenced by the variability of the conveyor belt (e.g., Gordon *et al*., 1992; Lehman, 1993). Numerical simulations of global ocean circulation show that small changes in the external forcing at high latitudes can switch off the present conveyor belt and force the ocean to reach another equilibrium state, in which the Antarctic Circumpolar Front represents the sole deep-water source (e.g., Maier-Reimer *et al*., 1993).

The North Atlantic atmosphere-ocean-cryosphere system appears to have natural cycles of many timescales in switching the conveyor belt. In these cycles, sea ice plays a pivotal role. Periodic movement of excessive sea ice from the Arctic into the Greenland Sea appears to be responsible for the interdecadal variability of the conveyor belt (Mysak *et al*., 1990), characterized by the freshening of the intermediate water (Dickson *et al*., 1988). There is no evidence yet that the influx of interdecadal switching extends beyond the North Atlantic Ocean.

Paleorecords show that 10,000 to 80,000 years ago there were millennial oscillations of several degrees of the sea-surface temperature in the North Atlantic (Bond *et al*., 1993; Figure 8-2), with abrupt temperature shifts in decadal timescales (Taylor *et al*., 1992). Interaction between the warm ocean surface current and the Scandinavian ice sheets is

Box 8-1 (continued)

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Figure 8-2: Ocean surface temperature in the North Atlantic over the past 80,000 years as inferred from sediment cores (top). These variations may be related to the strength of the "conveyor belt." When the conveyor belt is strong, as in the present, the North Atlantic polar front (i.e., the circulation boundary between cold polar and warm boreal water masses) swings open, allowing warm subtropical water masses to flow on to the north (bottom left). During the last glacial period, the conveyor belt was rapidly weakened many times due to iceberg surges (triangles in bottom right). Then the polar front swung to the east, cutting off the northward flow of warm waters (after Bond *et al*., 1993; Zahn, 1994).

thought to be the driving mechanism (Bond *et al*., 1993). These millennial cycles, called Dansgaard-Oeschger cycles, appear to lump into long-term cooling cycles (Dansgaard *et al*., 1993; Oeschger *et al*., 1984). Each cooling cycle culminates in an enormous discharge of icebergs into the North Atlantic from massive collapses of Laurentinide ice sheets—called a Heinrich event—followed by an abrupt shift to a warmer climate. The Younger Dryas—an event that happened at the last glacial termination about 11,000 years ago, when there were abrupt temperature decreases in Greenland and Northern Europe—also was a Heinrich event. Similar observations also have been made in the Greenland ice-core record from the last interglacial period (GRIP Project Members, 1993). In as much as the last interglacial seems to have been slightly warmer than the present one, global warming may destabilize the relatively stable climate that the Earth has experienced over the past 8000 years (GRIP Project Members, 1993). There is some doubt, however, about the reliability of the Greenland ice-core record for the last interglacial (e.g., Broecker, 1994). If the last interglacial climate variability did exist, it could have been due to an origin different from fluctuations in the strength of the conveyor belt (e.g., Zahn, 1994).

size—is actually not an efficient sink for increases in atmospheric carbon dioxide concentrations (e.g., Siegenthaler and Sarmiento, 1993). Nevertheless, the ocean is estimated to have taken up about 30% of carbon dioxide emissions arising from fossil fuel use and tropical deforestation between 1980 and 1989 (Siegenthaler and Sarmiento, 1993), thus slowing the rate of greenhouse global warming. The same estimate also leaves about 25% of the emissions unaccounted for. This "missing sink" for carbon dioxide is thought to be located in the terrestrial biosphere (Tans *et al*., 1990), although Tsunogai *et al*. (1993) suggest that the oceanic intermediate waters are also significant sinks for carbon dioxide.

The global ocean also plays a major role in the global hydrological cycle. The cycling of the oceanic freshwater fraction through advection, evaporation (E), precipitation (P), and—in higher latitudes—the solid-ice phase will be affected by changes in wind systems and oceanic current systems. The freshwater budget of the ocean is still not well enough understood, primarily because of the lack of adequate data, although Schmitt *et al*. (1989) have given some preliminary assessments. Atmosphere-ocean interactions maintaining the overall E-P balance will be affected by changes in circulation, evaporation, precipitation, and the availability of precipitable water in the atmosphere over the ocean. A changing pattern of rainfall over the oceans will cause changes in the rainfall pattern over land, which will in turn have a considerable effect on the salinity of marginal seas.

8.2.2. Resources and Products

The oceans provide living and nonliving (minerals and water) resources, opportunities for unconventional energy sources, pharmaceuticals, and marine electronic instrumentation.

8.2.2.1. Living Resources

Living resources include fish and shellfish, marine mammals, and seaweeds. In 1990, the world's fish catch was 97 million tons (mt)—14 mt from inland sources and 83 mt from marine sources (FAO, 1992a). However, the annual rate of growth in world marine catch has been declining since 1972 (FAO, 1992b). This decline in the rate of growth, and decline in overall production experienced in 1990, is the combined result of uncontrolled growth in fishing effort and overfishing of important stocks in the Atlantic Ocean. Uncontrolled access to resources and growth in fishing effort supported by large national subsidies are major weaknesses in the world fisheries system as a whole (see Chapter 16). In contrast, the production trend in the world aquaculture industry is the opposite of that in the marine capture fisheries industry. Between 1984 and 1992, world aquaculture production increased 89% and amounted to 23% of the world marine catch with a value of $32.5 billion (in 1992 U.S.$) (Aquaculture Magazine Buyers Guide, 1995). This subject is considered in Chapter 16.

A combination of human activities (e.g., overfishing, pollution of estuaries and the coastal ocean, and the destruction of habitat, especially wetlands and seagrasses) currently exerts a far more powerful effect on world marine fisheries than is expected from climate change. However, fisheries are indeed sensitive to climate change as inferred from paleorecords. The Working Group I report concludes that because marine photosynthesis is limited by nitrogen rather than by carbon, increasing CO_2 contents in the upper ocean is unlikely to have a positive impact on net primary productivity. Rather, primary productivity should respond to changes in nutrient availability resulting from changes in ocean circulation, runoff input, or atmospheric deposition. Because there is substantial uncertainty about whether any of these factors will change with global warming, it is not clear if average primary productivity will be affected. Even if global average primary productivity is negatively affected, there are so many pathways and loops in the chain between primary productivity and upper trophic level species—including a significant microbial loop—and regional conditions vary so widely that it is difficult to say whether reductions in the average yield of commercial fisheries will result.

There are indications that the potential value of the marine pharmaceutical industry is large, although there is no comprehensive study of the market for this industry. The oceans are a potentially enormous source of biological tissue that can be refined and developed into pharmaceuticals, enzyme preparations, gene probes, immunological assays, and new materials. Some of these materials have commercial potential in medicine, agriculture, marine aquaculture, and materials science.

The cleaning and disinfection of contaminated areas using microorganisms (bioremediation) is of potential importance in the oceans, largely on fixed surfaces such as sediments (Bragg *et al*., 1994; Swannel and Head, 1994). Bioremediation of the marine water column may not be important, largely because most contaminants in the oceans are particle-associated (e.g., sediment particles). Possible exceptions include highly contaminated seawater close to terrestrial hazardous waste disposal sites. To date, efforts to deal with these areas have been few.

The newest class of marine organisms that appears to have considerable commercial potential in the biotechnology industry is the hyperthermophiles (T_{opt} > 85°C) (Kristjansson, 1989). These bacteria live at extremes of pH and temperature that make them attractive to industry because, among other characteristics, they can yield long shelf-lives and tolerate organic solvents and harsh purification processes. Large colonies of hyperthermophiles now have been found at spreading centers in mid-ocean ridges (Jannasch and Wirsen, 1979), in the deep North Sea, and in Alaskan oil reservoirs (Stetter *et al*., 1993). However, they are difficult to culture in the laboratory. Not surprisingly, the potential value and availability of these hyperthermophiles have stimulated serious efforts to harvest them for industrial applications by biotechnology firms (e.g., Myers and Anderson, 1992).

8.2.2.2. Nonliving Resources and Unconventional Energy

The range of products in this category includes petroleum, placer and nearshore deposits (i.e., sand and gravel, sulfur, phosphorite), calcareous oozes including hot brines, manganese nodules, and polymetallic sulfides at spreading centers. The latter two are resources from the deep ocean bed, for which no large-scale commercial recovery has been attempted because it is presently uneconomic.

Petroleum hydrocarbons are by far the most significant contribution of the ocean to the world stock of nonliving (mineral) resources in both quantity and value. Offshore production is estimated to be approximately 26% of terrestrial production for oil, in amount and gross value, and 17% for natural gas (*Oil and Gas Journal*, 1993; *Offshore Journal*, 1993; Oil and Gas Journal Database, 1992).

Broadus (1987) estimates the annual gross value of all other extracted seabed minerals to be more than $600 million—of which tin is the most significant item and the only one that supplies more than 1% of its world market. Sand and gravel, calcium carbonate, sulfur, and other mineral placers are also among the seabed mineral resources that are actively extracted. The harvesting of precious coral, a combined living and mineral resource, supports an industry estimated to be worth more than $50 million a year (Broadus, 1987).

Other resources and products to be found in the ocean include water and unconventional energy resources. In the 1990s, more than 3,500 land-based desalination plants were in operation, producing more than 8 billion liters of water a day (Encyclopedia Britannica, 1993). Thirty percent of the total number of plants were located in the United States, and 20% were in the Middle East. Desalination of sea water is unlikely to be affected by global climate change.

Electricity from tidal power can be produced in only a few areas of the world (e.g., northern France and eastern Canada) where the tidal flux is sufficiently large. The total usable potential is estimated to be on the order of 200 million kW (Charlier and Justus, 1993). The potential for using temperature differentials in the tropical ocean between the surface and the water below the thermocline is quite large. This technique, called ocean thermal energy conversion (OTEC), theoretically can be applied in the latitude belt between 20°N and 20°S, but the area of greatest potential lies between 10°N and 10°S. Total potential electricity production from OTEC ranges between 10^8 and 10^{10} MW (Charlier and Justus, 1993). An upper limit per plant at the 10^7 MW level would amount to 299 quads per year [one quad = 10^{15} Btu (British thermal units)] of electric energy. So far, only two subsidized pilot plants have been in operation.

The oceans are an opaque, three-dimensional medium. The opacity derives from a limited capacity for penetration by either light or electromagnetic waves. The oceans also are characterized by storms, hazards to navigation, and currents of varying strength, so electronic means of sensing, communicating, and managing information are essential (Broadus *et al*., 1989). The major products here include communication and navigation instruments, sensors, data management instruments, and services. Navies, offshore oil and gas firms, oceanographic research and environmental monitoring entities, commercial shipping and fishing companies, and recreational boaters are the consumers of these products (Broadus *et al*., 1989). Initial estimates of the size of the world market for marine electronic instrumentation (Hoagland III and Kite-Powell, 1991) are in the range of $3–5 billion for the United States and roughly twice that size for the world (which includes the United States, Western Europe, and Japan).

8.2.3. Waste Reception and Recycling

Due to their enormous volume of water, microbial communities, and sediments, the oceans have the capability to receive, dilute, transform, eliminate, store, and recycle massive quantities of wastes from human activities conducted on land and in the atmosphere, as well as on water (Izrael and Tsyban, 1983, 1989; GESAMP, 1986). This capability to accept contaminants, however, is not limitless, and negative consequences can occur—especially in coastal seas and estuaries. The major sources and pathways of pollutants into the oceans are runoff and river inputs of land-based discharges, which contribute an estimated 44% (GESAMP, 1990); atmospheric deposition of land-based pollutants over the oceans, which contributes an estimated 33%; and at sea-activities, including mineral production, maritime transportation, and ocean dumping, which contribute 23% of the total inputs (GESAMP, 1990).

8.2.4. Recreation and Tourism

Recreation and tourism is an exceedingly large and rapidly growing market, which exceeded $2 trillion in 1986 (Miller and Auyong, 1991). Tourism accounts for more than 12% of the world's gross product and represents an important socioeconomic activity in the coastal environment (see Chapter 9). The organizational and operational facilities for the tourist industry—which include, for example, hotels, airports, ports, marinas, and the like—affect ecosystems such as estuaries, salt marshes, mangroves, seagrass beds, and other wetlands and coral reefs, all of which are already at risk due to pollution from human activities (Miller and Auyong, 1991). Maintaining a balance between developing tourism and recreation and preserving the aquatic environment is an issue affected by climate change because adverse human impacts on the coastal zone are likely to be amplified by the coastal effects of climate change (see Chapter 9).

8.2.5. Transportation

Transportation over water is by far the cheapest of all global transportation media available; consequently, more than 95% of world trade moves by ship. This medium is the least significant contributor of CO_2 per amount of product shipped. The world fleet in 1990 consisted of 424 million gross tons (GT, a volumetric measure) or 667 million deadweight tons (dwt, a measure of carrying capacity). Of that amount, exclusively cargo-carrying ships accounted for 46%; fishing vessels (all types >100 GT) accounted for 19%; and passenger vessels accounted for 18% (Lloyds Register, 1990). These three categories accounted for 83% of the world's fleet.

Marine transportation will be affected by climate change in three respects. First, in regions experiencing increased precipitation and runoff, increased dredging operations will be necessary in ports affected by increased sediment deposition. Second, if the frequency and uncertainty of tropical storms and hurricanes increases, shipping will be adversely affected, loss rates may increase, and freight and insurance rates will rise. Third, if the extent of sea ice is reduced by 20% in northern latitudes—which seems probable given that maximum warming is predicted to occur in high northern latitudes in winter (see the IPCC Working Group I volume, and Chapter 7)—then both the Northwest Passage and the Russian Northern Sea Route will become viable sea routes, thereby facilitating shipping and reducing costs between East Asia and Western Europe.

8.2.6. Information Function

In addition to the preceding functions and uses, the oceans represent a natural repository of genetic and biological information. One important effect of climate change is likely to be a net decrease in global biodiversity. In many cases, global warming will act in combination with other human factors—driving species to extinction, narrowing the genetic range within species, and transforming and simplifying ecosystems. Species that are rare, isolated on the edge of their tolerance, genetically impoverished, and in areas undergoing the most abrupt changes are likely to become extinct (Markham *et al*., 1993).

The biodiversity value of the ocean is particularly important because there are many groups of organisms, even at taxonomic levels above orders, that are exclusively marine. These animals and plants have special status in some ways related to biodiversity because the loss of these species represents a larger impact than the loss of species in widespread taxonomic groups.

8.3. Characteristics of Oceans and Their Responses to Climate Change

In this section we describe the major characteristics of oceans and their likely responses to global climate change scenarios.

8.3.1. Physical Characteristics

In the oceans, climate change will be accompanied by changes in temperature, circulation, sea level, ice coverage, wave climate, and extreme events. These changes are expected to have consequences for ecosystem structure and function, as well as for global biogeochemical cycles with feedbacks to the climate system.

8.3.1.1. Temperature

Studies of past climate changes show that sea surface temperature (SST) increases along with air temperature, although probably not as much as or as rapidly (IPCC, 1990a). Also, due to greater thermal inertia, changes in oceanic conditions will lag behind changes on the continents [e.g., by 10 years for the North Pacific (Wigley *et al*., 1985)]. The correlation between SST and land temperatures from a coupled ocean-atmosphere model suggests that SST will increase at a rate generally in line with the increase of mean land-temperature values (Manabe *et al*., 1991). Exceptions might occur in a belt around Antarctica and in the high-latitude North Atlantic. The modeled SST around Antarctica increases more slowly because of the upwelling deep-water masses. The predicted temperature increase in the high-latitude North Atlantic also is slower, apparently due to a weakening of the conveyor belt thermohaline circulation. The weakened conveyor belt could recover if atmospheric CO_2 concentration leveled off at double the present value but might never recover if it quadrupled (Manabe and Stouffer, 1993), driving the climate system into unknown directions. Exceptions also are expected to occur in arctic and subarctic regions, where the predicted warming may be higher than the global average.

8.3.1.2. Upwelling and ENSO Events

Divergence of wind-driven surface ocean currents induces upwelling of water from deeper layers. General circulation models (GCMs) predict a decrease of the meridional (north–south) gradients of sea-surface temperature due to significant warming in polar latitudes, which in turn would lead to a decrease in trade-wind intensity, the strength of the upper ocean currents (Mitchell, 1988), and the area and intensity of upwelling, such as in the equatorial eastern tropical Pacific. According to studies of paleoclimate, the productivity of open oceanic upwelling regions during glacial periods was much higher than during interglacial periods (e.g., Sarnthein *et al*., 1988; Lapenis *et al*., 1990). These studies indicate that global warming may be accompanied by a decrease in total productivity of the global ocean (Budyko and Izrael, 1987; Lapenis *et al*., 1990).

In contrast to model projections, however, observations over large parts of the tropical Atlantic between 1947 and 1986 have shown an increase in the trade winds (Bigg, 1993). Bakun (1990, 1993) suggests that the greenhouse effect will enhance the seasonal warming of continents—leading to a decrease in the pressure over land, an increase in the land–sea pressure difference, and increased alongshore winds. Binet (1988) has observed such effects along the coast of northwest Africa. It appears likely that the strength of both oceanic and coastal upwelling mechanisms could change under conditions of global warming, with profound impacts upon fish species and their production as well as on the climate of the immediate coastal zone (see also Chapter 16).

The El Niño-Southern Oscillation (ENSO) results from fluctuations in the internal interactions within the Earth's ocean-atmosphere system and is the most significant source of interannual variability in weather and climate around the world. The Southern Oscillation (SO) component of ENSO is an atmospheric pattern that extends over most of the global tropics. It principally involves a seesaw in atmospheric mass between regions near Indonesia and the Pacific Ocean region centered near Easter Island. The El Niño component of ENSO is an anomalous warming of the eastern and central tropical Pacific Ocean. In major "warm events," warming extends over much of the tropical Pacific and becomes clearly linked to the atmospheric SO pattern. ENSO events occur every 3 to 10 years, although in recent years the frequency has increased. The influence of ENSO sometimes extends to higher latitudes and has far-reaching climatic and economic consequences around the world (Ropelewski and Halpert, 1987; Zuta, 1986).

Although ENSO is a natural part of the Earth's climate, a major question is whether the intensity or frequency of ENSO events might change as a result of global warming. Historical and paleorecords reveal that ENSO events have changed in frequency and intensity in the past on multidecadal to century timescales (Nicholls, 1992; Anderson *et al*., 1992; Thompson *et al*., 1984). It is unclear whether ENSO might change with long-term global warming. Studies of long-term variations in ENSO using models have just begun (Knutson and Manabe, 1994; Kumar *et al*., 1994), and it is still premature to project the behavior of ENSO events for different climate-change scenarios.

8.3.1.3. Changes in Sea Level

The available estimates of sea-level changes under a changing climate are rather preliminary because of uncertainties both in the projections of climate change itself and in the assessment of the components that influence sea level. The latter include ocean thermal expansion, the effects of changing volumes of polar ice sheets and mountain glaciers, and dynamic effects resulting from ocean circulation, wind and weather patterns, and differences in regional ocean density (Box 8-2).

Revised projections, taking full account of both climate and sea-level components, are not yet available. However, indications are that both global warming and sea-level rise by the year 2100 may be 25–30% less than the IPCC 1990 projections (Wigley and Raper, 1992, 1993). Nonetheless, even the lower estimates of sea-level rise are about two to four times the rate of sea-level rise experienced in the last 100 years.

Rising sea level will have pervasive impacts for coastal zones and their ecosystems. A detailed analysis of the impacts of sea-level rise on the coastal zones may be found in Chapter 9.

8.3.1.4. Ice Cover

Sea ice covers about 11% of the ocean, depending on the season. It affects albedo, salinity, and ocean-atmosphere thermal exchange. The latter determines the intensity of convection in the ocean and, consequently, the mean timescale of deep-ocean processes affecting CO_2 uptake and storage.

Projected changes in climate should produce large reductions in the extent, thickness, and duration of sea ice. Major areas that are now ice-bound throughout the year are likely to have major periods during which waters are open and navigable. Some models even predict an ice-free Arctic (IPCC, 1990b). Melting of snow and glaciers will lead to increased freshwater influx, changing the chemistry of those oceanic areas affected by the runoff. At present, however, there is no convincing evidence of changes in the extent of global sea ice (Gloersen *et al*., 1992). Studies on regional changes in the Arctic and Antarctic indicate trends of decadal length (e.g., Mysak and Manak, 1989; Parkinson, 1992), often with plausible mechanisms proposed for periodicities of a decade or more. Thus, longer data sets are needed to test whether a genuine long-term trend is developing (see Chapter 7).

8.3.1.5. Wave Climate and Vertical Mixing

Winds and waves are the major forcing factors for vertical mixing; the degree of mixing depends on the vertical density structure. In the past 40 years, there has been an increase in the mean wave height over the whole of the North Atlantic, although it is not certain that global change is the cause of this phenomenon (Bacon and Carter, 1991).

In some permanently stratified anoxic basins, such as the Black Sea, climate change brings with it the possibility of turnover (Mee, 1992). The Black Sea has a very strong density gradient; the only risk of penetration of anoxic bottom waters to the surface would be by elevation of the oxic-anoxic boundary. Although this is controversial, Murray *et al*. (1989) have suggested that the oxic-anoxic boundary in the Black Sea has risen up to 30 m over the last 20 years in association with decreased river flows.

8.3.1.6. Extreme Events

The catastrophic aspects of storms and storm surges are well known, particularly in exacerbating flooding in coastal areas and in erosion and restructuring of coastal formations (see Chapter 9 for details). The causal relationship between sea-surface temperature and the formation of tropical cyclones suggests that the intensity and frequency of tropical cyclones may increase in the future. However, the evidence inferred from models based on such relationships is conflicting (Ryan *et al*., 1992; Stein and Hense, 1994). A GCM analyzed by Haarsma *et al*. (1993) showed that a doubling of CO_2 concentration increased by about 50% the number of simulated tropical disturbances, as well as

Box 8-2. Changes in Sea Level

Model projections suggest that in the oceans, temperature increase due to climate change is largest in the thermocline (Stouffer *et al*., 1989) but that the warming signal there is masked by eddies and seasonal variability. However, Bindoff and Church (1992) also found significant warming in the South Pacific below the thermocline, where the signal-to-noise ratio is larger (Figure 8-3). The corresponding sea-level rise caused by the thermal expansion of seawater is 2–3 cm over 22 years—consistent with the estimates of global sea-level rise. Under the predicted global warming, sea-level rise also will be accelerated by both warming of the ocean and possible melting of ice. A 40-cm global mean sea-level rise is projected by 2050 (see the IPCC Working Group I volume). However, global warming also will alter the variations in sea surface caused by dynamic effects resulting from wind and atmospheric pressure patterns, regional ocean density differences, and oceanic circulation (Figure 8-4). Large regional differences in sea-level response can be expected due to the effects of ocean circulation in sea-surface topography (Mikolajewicz *et al*., 1990). Increases in sea level would be highest in the North Atlantic; in certain regions, such as the Ross Sea, sea level actually would fall (Mikolajewicz *et al*., 1990). Regional differences in sea-level change are to be expected (see also Church *et al*., 1991; Cubasch *et al*., 1994). Therefore, there also will be significant regional differences in sea-level rise with global warming. In addition, it should be emphasized that for coastal environments, it is the relative sea level that matters [i.e., the level of the sea in relation to that of the land (see Chapter 9)].

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Keep Holding Line

Figure 8-3: The difference of the potential temperature between 1967 and 1990 across 43°S between Australia and New Zealand. The unit of the difference has been normalized by the root-mean-square variability (after Bindoff and Church, 1992).

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Drop Holding Line

Figure 8-4: Global variations of sea-surface topography (in mm) due to dynamic effects relative to the global mean sea level, as obtained from a transient experiment of increasing carbon dioxide concentrations using a coupled ocean-atmosphere GCM. The results are for years 66–75 of the model run (but cannot be ascribed to a future calendar date). The stippled areas on the map show sea-level rises that are less than the global average (after Gregory, 1993).

the number of intense disturbances, whose maximum windspeed increased by about 20%. The low resolution of the GCM calls for caution in interpreting the simulated changes in the intensity of tropical disturbances (Haarsma *et al.*, 1993). GCM results also indicate a change in cyclone tracks as a response to global warming. Bengtsson *et al.* (1994), on the other hand, report that with a doubling of CO_2 over the next 50 years, the global distribution of storms should be similar to the present geographical position and seasonal variability—although the number of storms is significantly reduced, particularly in the Southern Hemisphere. Tropical cyclone models require an initial disturbance to be present before a full-scale cyclone develops. A GCM, with its coarser horizontal resolution, cannot produce a better resolution than a cyclone model. Correlations also have been found between ENSO (as well as the southeast Asian monsoon) and the regional patterns of tropical cyclone activity (Nicholls, 1984; Evans and Allan, 1992). Unfortunately, it is not yet possible to say how ENSO, and thus tropical cyclones in these regions, will be affected by global warming (see also Section 8.3.1.2).

Although there is uncertainty, the extent of damage caused by great windstorm catastrophes has expanded in recent years. The concentrations of people living in high-risk coastal regions must be considered the main reason for this alarming trend (Berz, 1994). If storms intensify with rising temperatures, there will be adverse consequences for living and nonliving resource exploitation in the ocean and in coastal areas, for marine transportation, and for recreation and tourism. It must be noted, however, that scientific assessment of impacts in this context can differ from economic evaluation of loss because the methodologies used to assess loss are different. From a scientific perspective, damage or injury would be assessed in terms of the components and interrelationships in a particular ecosystem. From an economic perspective, however, loss is defined by value as determined by some market. It is therefore quite possible to get a scientific assessment of low injury to an ecosystem combined with high economic loss value, especially given that the value of waterfront real estate is normally high (see also Chapter 17). The reverse is also true: Major ecological damage might occur with little economic loss.

8.3.2. Ecological Characteristics and Biodiversity

Metabolic rates, enzyme kinetics, and other biological characteristics of aquatic plants and animals are highly dependent on external temperatures; for this reason alone, climate change that influences water temperature will have significant impacts on the ecology and biodiversity of aquatic systems (Fry, 1971). The capability of some species to adapt genetically to global warming will depend on existing genetic variation and the rapidity of change (Mathews and Zimmerman, 1990). Species remaining in suboptimal habitats should at least experience reductions in abundance and growth well before conditions become severe enough for extinctions to occur. The resilience of an ecosystem to climate change will be determined to a large extent by the degree to which it already has been impaired by other human activities.

Coastal ecosystems are especially vulnerable in this context. They are being subjected to habitat degradation; excessive nutrient loading, resulting in harmful algal blooms; fallout from aerosol contaminants; and emergent diseases. Human interventions also have led to losses of living marine resources and reductions in biodiversity from biomass removals at increasingly lower trophic levels (Sherman, 1994; Beddington, 1995; Pauly and Christiansen, 1995). The effects on biodiversity are likely to be much less severe in the open ocean than in estuaries and wetlands, where species in shallow, restricted impoundments would be affected long before deep-oceanic species (Bernal, 1991).

The chief biotic effects on individuals of an increase in mean water temperature would be increased growth and development rates (Sibley and Strickland, 1985). If surface temperatures were correlated positively with latitude, and temperature increased, one would expect a poleward shift of oceanic biota. While this may be the general case, there could be important regional variations due to shifts in atmospheric and oceanic circulation. The resulting changes in predator-prey abundance and poleward shifts in species' ranges and migration patterns could, in the case of marine fisheries, lead to increased survival of economically valuable species and increased yield. Such cases have been observed by Wooster and Fluharty (1985) as a result of the large and intense 1983 El Niño.

In high latitudes, higher mean water temperature could lead to an increase in the duration of the growing period and ultimately in increased bioproductivity in these regions. On the other hand, the probability of nutrient loss resulting from reduced deep-water exchange could result in reduced productivity in the long term—again highlighting the importance of changes in temperature on patterns of circulation. Global warming could have especially strong impacts on the regions of oceanic subpolar fronts (Roots, 1989), where the temperature increase in deep water could lead to a substantial redistribution of pelagic and benthic communities, including commercially important fish species.

For tropical latitudes, GCMs predict temperature increases that are half of those predicted for high latitudes, and the impacts in tropical latitudes are less clear. A 1.5°C increase would raise the summertime mean temperature to 30.5°C over much of the tropical and subtropical regions. Most migratory organisms are expected to be able to tolerate such a change, but the fate of sedentary species will be highly dependent on local climate changes. Some corals would be affected (as in the 1983 and 1987 bleaching events), but it is expected that other environmental stresses (e.g., pollution, sedimentation, or nutrient influx) may remain more important factors (e.g., Maul, 1993; Milliman, 1993). Intertidal plants and animals, such as mangroves and barnacles, are adapted to withstand high temperature, and unless the 1.5°C increase affects reproduction, it will have no effect. Similarly, only seagrass beds already located in thermal-stress situations (i.e., in shallow lagoons or near power plant effluents) are expected to be negatively affected by the projected temperature rise. One cannot rule out, however, the possibility of significantly greater tropical warming than 1.5°C. For example, some investigators argue that tropical warming was approximately 5°C from the last glacial maximum to today (Beck *et al*., 1992). If this value is correct, current GCMs probably underestimate tropical sensitivity.

Some algal species that are growing at the upper limit of their acceptable temperature range may be eliminated by a temperature increase of a few degrees in oceanic surface waters. There is no evidence that such increases will stimulate toxic algal blooms. Other factors, including competition for micro- and macronutrients, predation by zooplankton, and light-limitation, are of much greater significance to the growth rate and survival of marine algae. High levels of nutrients released into the coastal ocean from anthropogenic sources appear to increase the incidence and growth rates of many types of algae, including some toxic species (GESAMP, 1990). For instance, the toxic algae *Heterosigma spp*., which are responsible for fish kills in net-pen operations, have been linked to nutrient inputs in coastal waters in Japan (Insuka, 1985; Honjo, 1992).

Changes in temperature and salinity are expected to alter the survivorship of exotic organisms introduced through ballast water in ships, especially those species with pelagic larval forms. Introduction of exotic species is a form of biological pollution because, from a human perspective, they can have adverse impacts on ecosystems into which they are introduced and in some cases pose hazards to public health (International Maritime Organizations [IMO], 1991). A classic recent example of the spread of an introduced exotic species is that of the zebra mussel (*Dressena polymorpha*), which was transported to the Great Lakes via transatlantic shipping from the Baltic sea (Mills *et al*., 1993). Another recent example is that of the ctenophore, *Mnemiopsis leidyi*, which appears to have been introduced to the Black Sea from the east coast of the United States and has experienced explosive development since 1988 (Mee, 1992). Changes in temperature could enhance the potential for the survival and proliferation of exotic species in environments that are presently unfavorable.

Changes also can be expected in the growth rates of biofouling organisms that settle on means of transport, conduits for waste, maritime equipment, navigational aids, and almost any other artificial structure in the aquatic environment. Their species distributions often are limited by thermal and salinity boundaries, which are expected to change with regional changes in temperature and precipitation. Areas that experience warming and reduced precipitation (i.e., salinity increases) likely will have increased problems with biofouling.

Predicted climate change also may have important impacts on marine mammals such as whales, dolphins, and seals, and seabirds such as cormorants, penguins, storm petrels, and albatross. However, it is presently impossible to predict the magnitude and significance of these impacts. The principal effects of climate change on marine mammals and seabirds are expected from areal shifts in centers of food production and changes in underlying primary productivity due to changes in upwelling, loss of ice-edge effects, and ocean temperatures; changes in critical habitats such as sea ice (due to climate warming) and nesting and rearing beaches (due to sea-level rise); and increases in diseases and production of oceanic biotoxins due to warming temperatures and shifts in coastal currents.

Ice plays an important role in the development and sustenance of temperate to polar ecosystems because it creates conditions conducive to ice-edge primary production, which provides the primary food source in polar ecosystems; it supports the activity of organisms that ensure energy transfer from primary producers (algae and phytoplankton) to higher trophic levels (fish, marine birds, and mammals); and, as a consequence, it maintains and supports abundant biological communities (Izrael *et al*., 1992).

One of the possible beneficial consequences of global warming might be a reduction in the extent and stability of marine ice, which would directly affect the productivity of polar ecosystems. For example, the absence of ice over the continental shelf of the Arctic Ocean would produce a sharp rise in the productivity of this region (Izrael *et al*., 1992), provided that a sufficient supply of nutrients is maintained. Changes in water temperature and wind regimes as a result of global warming also could affect the distribution and characteristics of polynyas (ice-free areas), which are vital to polar marine ecosystems. In addition, changes in the extent and duration of ice, combined with changes in characteristics of currents—for example, the circumpolar current in southern latitudes—may affect the distribution, abundance, and harvesting of krill. Krill are an important link in the ocean fauna in the Southern Ocean. It is important to understand how, when, and where productivity in the Southern Ocean will change with global warming.

A number of marine organisms depend explicitly on ice cover. For example, the extent of the polar bear's habitat is determined by the maximum seasonal surface area of marine ice in a given year. The disappearance of ice would threaten the very survival of the polar bear, as well as certain marine seals. Similarly, a reduction in ice cover would reduce food supplies for seals and walruses and increase their vulnerability to natural predators and human hunters and poachers. Other animals, such as the otter, could benefit by moving into new territories with reduced ice. Some species of marine mammals will be able to take advantage of increases in prey abundance and spatial/temporal shifts in prey distribution toward or within their primary habitats (e.g., Fraser *et al*., 1992; Montevecchi and Myers, 1995), whereas some populations of birds and seals will be adversely affected by climatic changes if food sources decline (Polovina *et al*., 1994) or are displaced away from regions suitable for breeding or rearing of young (Schrieber and Schrieber, 1984).

Animals that migrate great distances, as do most of the great whales and seabirds, are subject to possible disruptions in the distribution and timing of their food sources during migration. For example, it remains unclear how the contraction of ice cover would affect the migration routes of animals (such as whales) that follow the ice front (Izrael *et al*., 1992). At least some migrating species may respond rapidly to new situations; for example, migrating ducks have altered their routes to take advantage of the recent exploding population of zebra mussels in the Great Lakes (Worthington and Leach, 1992).

While the impacts of these ecological changes are likely to be significant, they cannot be reliably forecast or evaluated. Climate change may have both positive and negative impacts, even on the same species. Positive effects such as extended feeding areas and seasons in higher latitudes, more-productive high latitudes, and lower winter mortality may be offset by negative factors that alter established reproductive patterns, breeding habitat, disease vectors, migration routes, and ecosystem relationships.

8.3.3. Biogeochemical Cycles

8.3.3.1. CO_2 Uptake and Biological Productivity

Climate change is expected to have an impact on processes controlling biogeochemical cycling of elements in the oceans, with potential feedbacks on various components of the carbon cycle. These impacts include the uptake of and storage capacity for CO_2 by physicochemical and biological processes. These aspects are considered in Chapter 6, *Climate Models—Projections of Future Climate*, and Chapter 10, *Marine Biotic Responses to Environmental Change and Feedbacks to Climate*, of the Working Group I volume.

Changes in sea-surface temperature can be expected to affect carbon chemistry both directly and indirectly. Changes will occur in the solubility of CO_2 and the remineralization of dissolved organic carbon. However, these changes are not expected to significantly affect atmospheric CO_2 concentrations (IPCC, 1994). Less certain, however, is the role of biological processes in sequestering carbon in the ocean and the potential impact of climate change on these processes.

The major process by which marine biota sequester CO_2 is thought to be controlled by nutrients, not by the concentration of dissolved inorganic carbon. A weakening of vertical and horizontal circulation as a result of warming (e.g., Manabe and Stouffer, 1993) could result in fewer nutrients in surface water, leading to a reduction of biological CO_2 uptake and storage (Volk and Hoffert, 1985). At the same time, less carbon-enriched deep water would be carried to the surface where the CO_2 is released to the atmosphere. The two effects result from the same process but affect the storage of carbon in opposite directions; they dominate models that use constant carbon-to-nutrient ratios to describe the marine biosphere (e.g., Bacastow and Maier-Reimer, 1990). These models project that a reduction of ocean circulation and vertical mixing will increase oceanic carbon storage slightly. A reduction in vertical mixing in the ocean also leads to a reduced downward transport of excess CO_2. It reduces the capacity of the oceans to store excess CO_2 because progressively less water is in contact with the surface over the period of atmospheric perturbation. Current model results suggest that the effects of predicted changes in circulation on the oceanic carbon cycle will not be large (Paillard *et al*., 1993). However, extrapolation of the long-term impacts of warming on circulation patterns has just begun; hence, the analyses of impacts on the carbon cycle must be viewed as preliminary.

Riebesell *et al*. (1993) claimed recently that phytoplankton growth rates are dependent on the availability of dissolved CO_2 and that this process could have been one of the factors responsible for changes in atmospheric CO_2 contents observed in the ice-core record. Their conclusions have been contested by other researchers who suggest that CO_2-limited photosynthesis cannot be equated with CO_2-limited growth rates (e.g., Turpin, 1993). Further research will be needed to ascertain whether increased CO_2 concentrations are likely to have the effects suggested by Riebesell *et al*. (1993).

Climate change also can affect the role of marine biota in other ways. Shifts may occur in the structure of biological communities in the upper ocean—for example, from coccolithophorids to diatoms—as a result of increased freshwater influx from melting ice and river runoff. This change will alter the ratio of organic carbon to carbonate carbon in the material settling out of the surface layers of the sea (Berger and Keir, 1984; Ittekkot *et al*., 1991). Biologically mediated carbon storage in the ocean is determined by the rate of transfer of organic matter from the surface layers, which exchange gases with the atmosphere, to the deep ocean, which remains isolated from the atmosphere for up to hundreds of years. The role of this transfer in the context of deep-sea carbon storage has not been adequately addressed in the scientific literature. Recent studies suggest that eolian dust and river-derived mineral matter can enhance carbon fixation at the sea surface by providing essential trace constituents such as iron (e.g., Martin and Fitzwater, 1987; Murray *et al*., 1994). Furthermore, this material can accelerate the transfer of organic matter to the deep sea by providing "ballast" material for rapidly sinking organic aggregates (Figure 8-5; Ittekkot, 1993). Thus, the efficiency of carbon storage in the deep sea may be affected by a changing climate and associated changes in atmospheric and ocean circulation and nutrient availability, combined with other global changes such as desertification. The magnitude and the direction of these changes remain unclear. Major national and international activities within the framework of JGOFS (Joint Global Ocean Flux Study) and GLOBEC (Global Ocean Ecosystem Dynamics) are expected to provide data to assess the role of biological processes in the removal of CO_2 from the atmosphere into the depths of the oceans.

Most of the organic-carbon burial in modern marine sediments on a global basis occurs in deltas and continental-margin environments (Berner, 1992) that are characterized by inputs from high primary productivity and terrigenous material discharged by the rivers. Both inputs are likely to be influenced by climate change affecting carbon cycling in these regions, with feedbacks to the carbon cycle and hence climate. It is difficult at present to assess the nature and extent of such an influence because other factors such as nutrient loading and river runoff

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Figure 8-5: Schematic of processes that control organic-matter production and removal to the deep sea (“the abiotically driven organic carbon pump” in the ocean). Dust particles deposited at the sea surface not only introduce essential trace nutrients such as iron (stimulating primary productivity), but also become incorporated into organic aggregates that form high-density particles (the ballast effect) with faster sinking rates—thus accelerating the transfer of newly fixed carbon dioxide to the deep sea. Strong winds enhance the effect as well. The efficiency of this transfer—therefore of carbon storage in the deep sea—is expected to be affected by global warming (after Ittekkot, 1993).

already have a strong impact in these areas and because the role of coastal oceans in the global carbon cycle is poorly understood (Smith and MacKenzie, 1991).

Marine aerosol formation is associated with the production of dimethyl sulfide (DMS) by specific phytoplankton species in the ocean (Charlson *et al*., 1987). DMS is the most important source of cloud condensation nuclei (CCN). Changes in phytoplankton species due to predicted global warming can have other feedbacks in the climate system, although the direction and quantitative significance of such feedbacks have to be assessed. The role of the oceans in the contribution of other greenhouse gases to the atmosphere—such as, for example, methane and nitrous oxide—is just beginning to be assessed, and the impact of climate change is still uncertain (see Chapter 10, *Marine Biotic Responses to Environmental Change and Feedbacks to Climate*, of the Working Group I volume).

8.3.3.2. Contaminant Distribution and Degradation

Contaminant distribution in the ocean will be especially sensitive to climate change because two major pathways of pollutants into the oceans will be affected: river runoff and atmospheric transport. The impacts of global warming on coastal and ocean pollution can be expected to depend on the way global warming will affect the nature and concentrations of pollutants in question, as well as on changes in their persistence in the environment. Changes in the cycling and distribution between phases (dissolved versus sedimentary) could occur under a global warming scenario for sewage, organics, organochlorines, and heavy metals (e.g., Tsyban *et al*., 1990). In most cases, phase transitions can be expected. A rise in temperature also may result in accelerated biodegradation of global organic pollutants (petroleum and chlorinated hydrocarbons, etc.). This process would promote their removal from the biologically active surface layers of the ocean (Izrael and Tsyban, 1989; Tanabe, 1985). However, the fate of degradation products is less well-known, and there also is the possibility of an increase in the toxicity of at least some of the pollutants under such conditions and with higher temperature. Further, the impact of climate change can be expected to be more severe in coastal seas and landlocked marine basins—such as, for example, the Baltic Sea and the Black Sea, which are already seriously impacted by pollution from human activities.

8.3.4. Socioeconomic Systems

The institutional structure of socioeconomic systems is an extremely important determinant of behavior, and it accounts for relative success or failure in system performance (Ostrom, 1990; Haas *et al*., 1993; Lee, 1993; Putnam, 1993). Institutional structure includes, among other characteristics, patterns of social organization and the distribution of authority.

A survey of the patterns of current social organization on a global basis, however, shows that present patterns and system capabilities are inadequate to respond to climate change. The major drawback is a lack of integrative capacity even at national levels concerning the use of the coastal ocean and even more so with reference to the exclusive economic zone (EEZ) as a whole (Underdal, 1980; Miles, 1989, 1992). This lack of integrative capacity arises because patterns of ocean use have developed largely in isolation from each other and because different technologies have given rise to separate networks, communities, and ways of thinking and doing. These communities have matured into almost fully autonomous sectors, with only weak or no links among them. These sectors are still needed for specialization. What is missing, however, is an integrative overlay in the institutional structure to assess a country's interest in the ocean as a whole and to make judgments about long- and short-term priorities and responses.

8.4. Impacts of Climate Changes on Resources and Products

The potential effects of climate change on resources and products range from significantly negative to significantly positive. These effects and the probability of their occurrences are listed below:

- **Significantly Negative**
  - A predicted 2°C average global atmospheric temperature increase by 2050 will result in increased coral bleaching, which in turn will result in a reduction in coral production. *Rating*: Very probable.
  - Increased precipitation, river runoff, and atmospheric deposition from land-based activities will lead to increased loading of pollutants in coastal waters and an adverse impact on fisheries, coral production, and recreation and tourism. *Rating*: Very probable.
  - If the frequency of tropical storms and hurricanes increases, there will be adverse impacts on offshore oil and gas activities in certain locations and on marine transportation. *Rating*: Uncertain.
- **Mildly Negative**
  - There will be problems in the operation of low-head tidal power plants due to increased sedimentation from increased precipitation and runoff in the Northern Hemisphere. There also will be reduced potential for OTEC in certain locations due to a reduction in differential between surface temperature and temperature below the thermocline. *Rating*: Very probable.
  - There will be increased costs generated by the need to expand dredging operations to keep major ports open in particular locations. *Rating*: Very probable.
  - There will be reduced fisheries yield if average primary productivity decreases. *Rating*: Uncertain. This effect probably will be dwarfed by the combined adverse impacts of overfishing, marine coastal pollution, and habitat destruction. *Rating*: Virtually certain.
- **Neutral**
  - Marine pharmaceutical and biotechnology industries are unlikely to be affected by climate change. *Rating*: Very probable.
  - Nonliving resource exploitation other than petroleum hydrocarbons will not be affected by climate change. *Rating*: Very probable.
- **Mildly Positive**
  - There will be growth in the marine instrumentation industry to facilitate research and monitoring of climate change through expanding capabilities for automatic sensing. *Rating*: Virtually certain.
- **Significantly Positive**
  - There will be increased growth and yield of upper-trophic-level species in commercial fisheries, but this effect will be dwarfed by current overfishing, marine pollution, and habitat destruction. *Rating*: Uncertain.
  - The Northwest Passage and the Northern Sea Route of Russia will be opened for routine shipping, reducing freight rates between East Asia and Western Europe. *Rating*: Very probable.

8.5. Evaluation of the Impacts of Climate Change

8.5.1. Resources and Products

In this chapter, the notion of mitigating impacts includes techniques of prevention or reduction in the scope or intensity of predicted effects. Adaptation means coping with or compensating for the rate of damage.

8.5.1.1. Significantly Negative Impacts

Reported incidences of coral bleaching appear to be increasing in association with more-frequent ENSO events since 1982–83 (Glynn, 1989; Brown and Ogden, 1993). Coral mortality is positively correlated with the intensity and length of warming episodes (Glynn, 1989; Glynn and Croz, 1990), and recent paleoclimatic investigations of ENSO phenomena show that the coral record can be read as a proxy for increased SSTs, potentially over several thousand years (Cole *et al*., 1992; Shen, 1993). Corals thrive in a temperature range of 25–28°C, but experimental and observed evidence indicates that mortality can be induced with even a 5°C increase in SST if exposure is prolonged beyond six months (Glynn and Croz, 1990). The time required to induce mortality decreases as SST increases along a gradient of 1–4°C (Glynn, 1989).

Therefore, assuming a 2°C increase in average global temperature by 2050—as predicted by Working Group I—it is doubtful that either mitigation or adaptation would be possible. The magnitude of such an increase, in addition to the rapid rate of change, leaves virtually no margin for corrective action. If maximum temperatures in the tropics exceed an increase of 3°C for extended periods, the impact will be severe. Moreover, corals are already at risk from a wide variety of human activities on land and at sea. This additional risk severely compounds the problem.

Independent of coral bleaching, increased loading of land-based pollutants in the coastal ocean as a result of increased precipitation and atmospheric transport can be mitigated by significantly reducing current loading of land-based pollutants in the marine environment. This very difficult problem has received some scientific and legal attention at global and regional levels since the Stockholm Conference in 1972 and a great deal more since the UN Conference on Environment and Development in Rio de Janeiro in 1992. Indeed, a major international conference on land-based pollution of the marine environment was convened by the United Nations Environment Program (UNEP) in October 1995.

The legal infrastructure at the global level for combating land-based pollution of the marine environment appears to be adequate. The problems to be solved are increasing compliance with existing legal obligations and developing scientifically based policies that effectively respond to the land-based pollution problem (GESAMP, 1990). Effective regulation must be based on an understanding of the fate and transport of contaminants over space and time and the damage caused by these pollutants to the structure and function of aquatic ecosystems. Significant issues include the persistence of contaminants in the aquatic environments, their uptake by commercially important fish and shellfish, the nature of sublethal effects to marine and freshwater organisms, and the risk to humans (Capuzzo, l990).

In addition, competing legislative and institutional structures at national, regional, and global levels need to be harmonized and rationalized in order to avoid the inconsistencies in policy derived from piecemeal attempts to solve problems. In the formulation of policies, priority must be given to the most-toxic waste streams in order to curtail long-term damage. In this connection, it is important to focus particularly on nonpoint sources of pollution, especially agricultural and urban runoff, and to avoid placing the greatest burdens on estuaries and the coastal ocean. Policy formulation might most effectively emphasize risk assessment and risk management—in support of which the development of long-term monitoring capabilities and standardized databases will be particularly important (GESAMP, 1991).

If the frequency of tropical storms and hurricanes increases, there are no mitigating options available for either the offshore oil and gas industry or the shipping industry. The former will have to adapt by improving the design standards for offshore structures. For marine transportation, the issue of whether the frequency of storms increases is an important question that will affect ship operations, equipment, maintenance, and insurance. One possible adaptation may be in national regulations to avoid areas that are too dangerous or will put biological communities at risk—along with the technological means to provide early warning at sea. If the occurrence of extreme events increases, governments have the option of increasing the attention given to issues of institutional design to respond to disasters and acute emergencies, planning for such responses, and introducing effective training of personnel (Drabek, 1985, 1989).

8.5.1.2. Mildly Negative Impacts

Mitigation and adaptation options are available for the mildly negative impacts. Because the minimum temperature differential required for OTEC plants is 20°C (Charlier and Justus, 1993), the crucial question is to what extent the intermediate water will warm relative to the surface. Should the temperature differential become unfavorable, two corrective measures are at least theoretically possible for floating power plants: relocate the plant, or increase the depth of the cold-water pipe. However, both of these options are seriously constrained by cost, and increasing the depth of the pipe imposes maintenance requirements that are severe below about 450 m (Charlier and Justus, 1993). For marine transportation, if major ports experience significant increases in sediment deposition via river runoff, dredging is the obvious option—with associated increases in the costs of operation.

There is uncertainty with respect to the impact of increased global average temperature of magnitude 2°C on primary productivity, but much less so on the growth and development of species at higher trophic levels. However, the impact of global warming can be swamped by the combined effects of overfishing, increased marine pollution, and habitat degradation/destruction. Again, in this case both mitigation and adaptation options are available.

As detailed in Chapter 16, changes must be made in approaches to management so that fishing effort is controlled and sized to available resources. Control over land-based pollution of the marine environment, combined with control over habitat degradation/destruction, also will go a long way toward creating an environment in which fisheries can prosper.

Moreover, in marine ecosystems where the fish community has been altered through excessive fishing effort—causing cascading effects up the food chain to top predators and down to first and second trophic levels—it is possible to facilitate recovery of depleted species through the introduction of adaptive management techniques (e.g., Sherman, 1994).

8.5.1.3. Neutral Impacts

Except for hydrocarbon extraction in polar areas, marine mineral extraction will be largely insensitive to an increase in average global temperature on the order of 2°C. Hence, mitigation and adaptation options are not required. Similarly, the source material for biotechnological/biomedical uses will not be affected by global warming, because most marine organisms living in the upper layers of the ocean can and do tolerate some degree of seasonal variations in temperature. Those living in the more-constant temperature depths are unlikely to be affected. Global warming will not have an effect on bioremediation applications. The most likely response to higher temperatures will be an increase in growth rate (hence, clean-up rate) of the organisms involved. It must be noted, however, that the changes in biodiversity due to global warming can be expected to have a certain degree of impact on these industries.

8.5.1.4. Mildly Positive Impacts

There is no need for mitigation of the mildly positive impacts of global warming; the market-driven need will create its own adaptation, to which the marine instrumentation industry will respond. Growth within the marine instrumentation industry generated by the need to monitor climate change will be reflected in the design of new sensors to facilitate observation, measurement, and monitoring, as well as the adaptation of existing platforms to perform new functions. For instance, offshore oil and gas platforms are now seen as having value for monitoring dimensions of climatic change (MTSJ, 1993). The U.S. National Oceanic and Atmospheric Administration (NOAA) has organized the cooperation of platform operators into a network to provide time-series measurements for the Global Ocean Observation System (GOOS) program in the Gulf of Mexico. Such adaptation appears to be extremely cost-effective.

8.5.1.5. Significantly Positive Impacts

Existing human-induced problems will swamp the significantly positive impacts of global warming on fisheries, and the same mitigation options outlined in Sections 8.5.1.1 and 8.5.1.2 relative to negative impacts on fisheries will apply in this case.

On the other hand, opening up the Northwest Passage and the Russian Northern Sea route for routine shipping for as much as 100 days a year (see Chapter 7) will provide significant benefits to many countries in terms of efficiency and speed of service and cost reduction that could translate into lower freight rates. At the same time, because both transportation and hydrocarbon exploitation will be facilitated by the reduction in ice cover in polar seas, the development of these regions for transportation and resource exploitation should be approached with great care. Stringent controls on pollution of these newly accessible regions will be necessary because ice will still retard clean-up possibilities for more than 200 days per year.

8.5.2. Ecology and Biodiversity

In some cases, no reliable adaptation is possible for changes in ecology and biodiversity. For example, for large mammals affected by the loss of ice cover, such as polar bears, no adaptation at all will be possible because of the loss of territory and loss of prey. In cases where adaptation options are available, they will vary according to the scale of the changes. If, for example, there is extirpation of a species, then carefully planned reintroductions may work. Survival of the species will then depend on the elimination of the stress factors that caused their extirpation. In the case of global extinctions, there is no adaptation possible. The consequences of an artificial restructuring of an ecosystem or community are at present unpredictable.

In the case of increases in species, eliminating successful exotics is rarely possible. Although the introduction of exotic predators is one possible option, our ability to predict the effects of such introductions is lacking. Depending on management goals, there could be successful introduction of exotics that make the system more useful to humans.

8.5.3. The Issue of Costs

Critical to any discussion of adaptation options is the issue of costs. However, at present we do not have sufficiently detailed knowledge of the costs of the most important impacts of climate change on the human uses of the oceans and the available options to mitigate and adapt. Some of the impacts of global climate change are beneficial, some are neutral, and some are adverse. The costs and benefits will be transferred and/or apportioned either by governments or by markets, or by some combination thereof. Such transfers will have price effects, which could affect the competitiveness of ocean industries in relation to each other and their competitors on land. In some cases (e.g., the impacts of sea-level rise), the total burden of cost transfers is likely to be greatest on those least able to bear them (i.e., the poorest countries). It is likely that costs will vary in a nonlinear fashion, sometimes rising much more steeply than the temperature increase with time, especially for flood damages or agricultural impacts.

The point about the competitiveness of ocean industries in relation to their competitors on land requires further elaboration. By and large, it is more costly to work on the ocean than it is on land, and the risk is generally higher. Whether one is dealing with nonliving resources or any other kind of product, the critical issues are relative scarcity, substitutability of materials/products, extension of available resources as a result of technological innovation, or location and exploitation of previously uneconomic resources (Broadus, 1987). Increasing reliance on more costly resources tends to raise the price of extracted materials—prompting substitution, conservation, recycling, and exploration (Broadus, 1987).

Increasing or decreasing scarcity of resources is best reflected in the long-term market price (Broadus, 1987). However, if the practical utilization of a marine resource lies more than two decades into the future, the net present value of that resource is essentially zero because firms will consider that they do not have sufficient control over the relevant factors controlling the cost of production and therefore price. The market's reluctance to act in these circumstances does not mean that nothing will be done. For strategic reasons, some governments may wish to subsidize exploration and even exploitation for varying lengths of time in some of these cases.

8.6. Multistress Factors

We have made the point that the coastal ocean is already under stress as a result of a combination of factors (e.g., increased population pressure in coastal areas, habitat destruction, increased land-based pollution, and increased river inputs of nutrients and other pollutants). In addition, increased UV-B radiation due to stratospheric ozone depletion is expected to impair the resilience of aquatic ecosystems to climate change. Smith *et al*. (1992) demonstrate that increased UV-B radiation has the effect of causing an estimated 6–12% reduction in primary productivity in the surface waters of the Southern Ocean during Austral spring. McMinn *et al*. (1994) conclude, on the other hand, that thick ice cover and the timing of the phytoplankton bloom in the Southern Ocean protect the phytoplankton from the adverse effects of increased UV-B radiation. A more comprehensive treatment of the subject is given by the Ozone Trends Panel (OTP).

Also of importance in the context of the impact of global warming is the debate about whether the phenomenon of coral bleaching is an effect solely of increased water temperature or increased UV-B radiation in the 280–400 nm band. Recent results suggest that bleaching of corals by increased UV-B radiation and by the temperature of surface waters appears to be independent of each other (Gleason and Wellington, 1993). These results are challenged, however, by Dunne (1994), who argues that the experimental controls do not conclusively rule out other factors such as the impact of photosynthetically active radiation (PAR) or synergistic effects between PAR and UV-B radiation on bleaching.

The effects of global climate change therefore will constitute a mixed series of impacts on an already overstressed context, with attendant opportunities for synergistic relationships between the stresses where the climate-change impacts are adverse. Synergy will accelerate the adverse impacts of these stresses. These burdens present a challenge and increase the urgency for the development of integrated coastal management responses at regional and global levels.

These multistress factors also make coastal areas much more vulnerable than the open ocean. Coastal states therefore may wish to consider controlling population density, habitat destruction, and land-based pollution. In this connection, the combination of existing trends of human-induced stress on the coastal environment with potential stresses generated by global climate change requires building the capability for planners and analysts to provide cumulative, integrated impact assessments (Gable *et al*., 1991). Databases to facilitate such assessments do not yet exist and need to be built. The criteria for designing such databases include the need to "evaluate the exposure, response, risk, and vulnerability of cultural, economic, social, biological, and physiographical implications of global change and its local, basin-wide, regional, and interregional manifestations"; the cumulative effects of environmental variability on various time and space scales; the effects of minor but collectively significant events occurring over long timescales; and the potential for synergistic effects of interacting combinations superimposed on direct effects (Gable *et al*., 1991).

8.7. Research and Monitoring Needs and Strategies

In this section, we consider research and monitoring needs that will allow better understanding of the characteristics and functions of oceans that are most likely to be affected by a projected climate change; development of methodologies to assess the sensitivity of oceans to climate change; and formulation of pilot studies on potential impacts, thresholds and sensitivities, and mitigation/adaptation strategies:

- *Research activities to better understand processes in the oceans*, in particular the role of the oceans in the natural variability of the climate system at seasonal, interannual, and decadal to century timescales; the role of the Atlantic Ocean in climate variability; the role of the ocean in the hydrological cycle; the role of biological and biogeochemical processes in transient—decades to centuries—carbon storage in the deep sea
- *Long-term monitoring and mapping of*: water-level changes, ice coverage, and thermal expansion of the oceans; sea-surface temperature and surface air temperature; extratropical storms and tropical cyclones; changes in upwelling regimes along the coasts of California, Peru, and West Africa; UV-B radiation, particularly in polar regions, and its impact on aquatic ecosystems; regional effects on distribution of species and their sensitivity to environmental factors; changes in ocean biogeochemical cycles. These activities allow for better understanding of the processes that affect the stability and vulnerability of marine ecosystems and their spatial and temporal variability. They also allow for better assessment of climate change-induced rates and the direction of changes and processes in oceans that already are impacted by other factors.
- *Socioeconomic research activities* to document human responses to global environmental change, such as the establishment of databases on patterns of human responses to global and regional environmental changes; the assessment of the transfer costs and economic effects of global and regional climate change; the development of alternative approaches to mitigation and adaptation, as well as policy design; and assessment of the synergistic effects of sectoral approaches to policy implementation
- *Strategies for implementation* of these monitoring and research needs could include national and international environmental and climate research programs to

consider research and monitoring components specifically designed to investigate the impact of climate change, taking into account the specific regional and national needs based on the pattern of the respective human response to global and environmental changes; and formal coordination between IPCC and other international environmental and climate research and monitoring activities organized by, for example, the International Geosphere-Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP), to pool expertise and efforts to better monitor aspects of climate change and its impacts, as well as to formulate policy options. Because modeling and monitoring depend on actual knowledge and technological capabilities, there also is considerable room for improvement in the level of communication between modelers and monitors in order to improve the state of the art and prediction capabilities.

It must be noted that research programs, by definition, are focused on a topic or problem, have an underlying approach, and promise results in a given time and funding frame. Furthermore, research topics change over longer times. In contrast, monitoring must be protected from such changes because the use of time series depends on the absence of changes in data-collection methods. Institutional research or scientific establishments with a longer breadth, such as government research laboratories, need to be encouraged to get their particular expertise rolled out: long-term maintenance of monitoring and research programs. Especially in view of the need to support long-term observations (observing systems such as GOOS, GCOS, GTOS, etc.) and the complex nature of the issues at hand, it will be necessary to pool the expertise and efforts of individual research institutions and governmental research laboratories actively and intimately.

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